

## STREAM HEALTH RANKINGS PREDICTED BY SATELLITE DERIVED LAND COVER METRICS<sup>1</sup>

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**ABSTRACT:** Land cover and land use change have long been known to influence the chemical, physical, and biological characteristics of streams. This study makes use of land cover maps derived from fine resolution satellite imagery and an extensive stream quality dataset to determine the relationship between small watershed health rankings and land cover composition and configuration. Landscape metrics were derived from digital impervious surface area (ISA), tree cover (percent), and agricultural crop maps within Montgomery County, Maryland. Watershed rankings were developed by state and county collaborators (MD-DNR and MCDEP) using extensive biological and chemical measurements. In stepwise logistic regression models the factors accounting for the most variation in stream health ranking were the percent ISA, followed by the percent of tree cover. Riparian buffer zone tree cover was also a significant predictor. Of the metrics that considered the spatial configuration of the landscape, a contagion index and the percent of ISA in the flow path from the ISA to the stream were also found to be significant predictors of stream health. Despite limited ability to characterize landscape configuration or narrow riparian buffer zone vegetation with coarser resolution imagery (from Landsat), model results were not significantly different from those based on the use of fine-resolution ISA information, suggesting that broader area applications of the approach are possible. The results indicate that management practices designed to improve stream water quality should focus on the amount of ISA and tree cover in both the watershed and within the buffer zone.

(KEY TERMS: land use planning; remote sensing; restoration; riparian buffers; stream health; urbanization; water quality; watershed management.)

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## INTRODUCTION

The National Academy of Sciences has identified land cover and land use change as one of the primary drivers affecting ecological systems (NRC, 2001; U.S. Global Change Research Program, 2003). Freshwater systems are especially vulnerable to land use change, particularly the increased urbanization occurring across much of the nation, which has contributed to changes in aquatic community structure and degradation of stream biota (e.g., Wang *et al.*, 2001; Nilsson *et al.*, 2003). Currently more than 70 percent of freshwater mussels, 55 percent of crayfish, 42 percent of amphibians, and 40 percent of freshwater fishes are either vulnerable, imperiled, or critically imperiled in the United States (USEPA, 2002). In the Chesapeake Bay watershed, numerous studies have demonstrated the association between land use changes and the degradation of the biological, chemical, and physical quality of streams (Liu *et al.*, 2000; Jones *et al.*, 2001; Palmer *et al.*, 2002; Paul *et al.*, 2002). In the State of Maryland 46 percent of all streams are in poor condition, based on a combined macroinvertebrate and fish Index of Biological Integrity (IBI), and the proportion of urban land cover is expected to increase to between 16 and 21 percent of total land area within the next 25 years (Boward *et al.*, 1999). In the greater Baltimore-Washington, D.C., region, urban and residential lands surrounding the Chesapeake Bay have increased by 63 percent in the 15 years from 1986 through 2000, and a predictive model calibrated with these results estimates an additional 80 percent

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expansion will occur by the year 2030, assuming current trends continue (Jantz *et al.*, 2003).

The altered composition and configuration of land use, such as expansion of impervious surface areas and conversion to agriculture within a watershed, can negatively affect the hydrology, geomorphology, chemistry, and ecology of stream ecosystems (Townsend *et al.*, 1997; Weller *et al.*, 1998; Wang *et al.*, 2001). The infiltration of rainwater and snowmelt into the ground is inhibited by impervious surfaces created when land is developed. As this impervious surface area increases, watershed base flows are reduced and flood discharge frequency and magnitude increase because of the combination of reduced infiltration into ground water and increased overland flow (Brun and Band, 2000; Jennings and Jarnagin, 2002). The connection of impervious surface areas across the landscape produces flashier stream hydrographs that exhibit a decreased lag time between storm events and peak discharge (Moglen and Beighley, 2002). Stream channels are modified by these changes in streamflow, including increased bank and stream bed incision, which exacerbates erosion and associated sediment loads (Schueler, 1994; Palmer *et al.*, 2002). Additionally, increasing impervious surface area has long been known to increase point source pollution discharges into streams, including chemical runoff from parking lots and roads (Wilbur and Hunter, 1979; Arnold and Gibbons, 1996).

The conversion of naturally forested watersheds to crop and pasture results in similar deleterious effects on stream ecosystems. Elevated levels of nonpoint source nutrients in streams, including nitrogen and phosphorous, are often associated with agricultural land uses (Jordan *et al.*, 1997a; Townsend *et al.*, 1997; Sonoda *et al.*, 2001). Fertilizer used on lawns, crops, and septic tank leakage are other known contributors to nutrient concentrations in streams (Jordan *et al.*, 1997b; Wernick *et al.*, 1998). Conversion of natural land cover to agricultural and urban uses can alter the temperature of the instream habitat by direct input of runoff warmed by contact with paved surfaces and by reduced shading from riparian vegetation (Schueler, 1994; Sliva and Williams, 1997; Brinson *et al.*, 2002). Many studies have shown the effectiveness of riparian buffers in abating nonpoint source pollution, but measuring stream integrity and the effectiveness of intact riparian buffers requires extensive and expensive field monitoring (Jordan *et al.*, 1993; Osborne and Kovacic, 1993; Weller *et al.*, 1998; Stauffer *et al.*, 2000; Reed and Carpenter, 2002).

Biological monitoring tools have been developed that integrate information on biological communities, including key indicator species (Klauda *et al.*, 1998; Diamond and Serveiss, 2001). Biological monitoring can detect anthropogenic influences and degradation

in a stream where none would otherwise be apparent if only chemical and physical stream assessments were performed (Karr, 1991). Since the development of the Index of Biological Integrity (Karr, 1981), larger and more standardized databases on stream health have been compiled (USEPA, 2002; Strayer *et al.*, 2003), allowing more comprehensive association with land cover information (e.g., Kennen, 1999; Basnyat *et al.*, 2000; Meador and Goldstein, 2003). Similar advancements in monitoring land cover with satellite image data permit improved characterization of the links with stream health, including the potential influence of landscape configuration (e.g., Roth *et al.*, 1996; Jones *et al.*, 2001; Stewart *et al.*, 2001; Goetz *et al.*, 2003).

The objectives of this study were to utilize fine resolution land cover and landscape configuration information derived from very high resolution satellite imagery for a range of small watersheds in suburban Maryland, to explore their relationship with stream health. The stream health rankings were derived from a combination of physical measurements and macroinvertebrate and fish biological indices. This was approached by developing logistic regression models of stream health rankings, incorporating the heterogeneous land cover types, topographic information, and the spatial configuration of landscape variables.

## DATASETS AND METHODS

### *Study Site*

Montgomery County, Maryland, is part of the Baltimore-Washington metropolitan area and in 2003 was home to 810,000 people (Figure 1; MCDEP, 2001). Originally forested, the 1,283 square kilometers of the Montgomery County landscape has undergone several cycles of land cover change. In the 1800s, land clearing for timber and agriculture occurred, followed by abandonment and natural reforestation, and then by the current rapid population growth and accompanying development of urban and suburban areas. Currently, "developed" land covers 21 percent, agricultural land 13 percent, forested land 43 percent, and other land cover (e.g., recreational grass, bare ground, water, etc.) 23 percent of the county (Goetz *et al.*, 2004).

Forty-eight species of fish and 140 types of aquatic insects inhabit the 1,500 miles of open stream within Montgomery County (MCDEP, 2001). At the 11-digit Hydrologic Unit Code (HUC) scale, the streams flow within 10 distinct watersheds: Monocacy River,

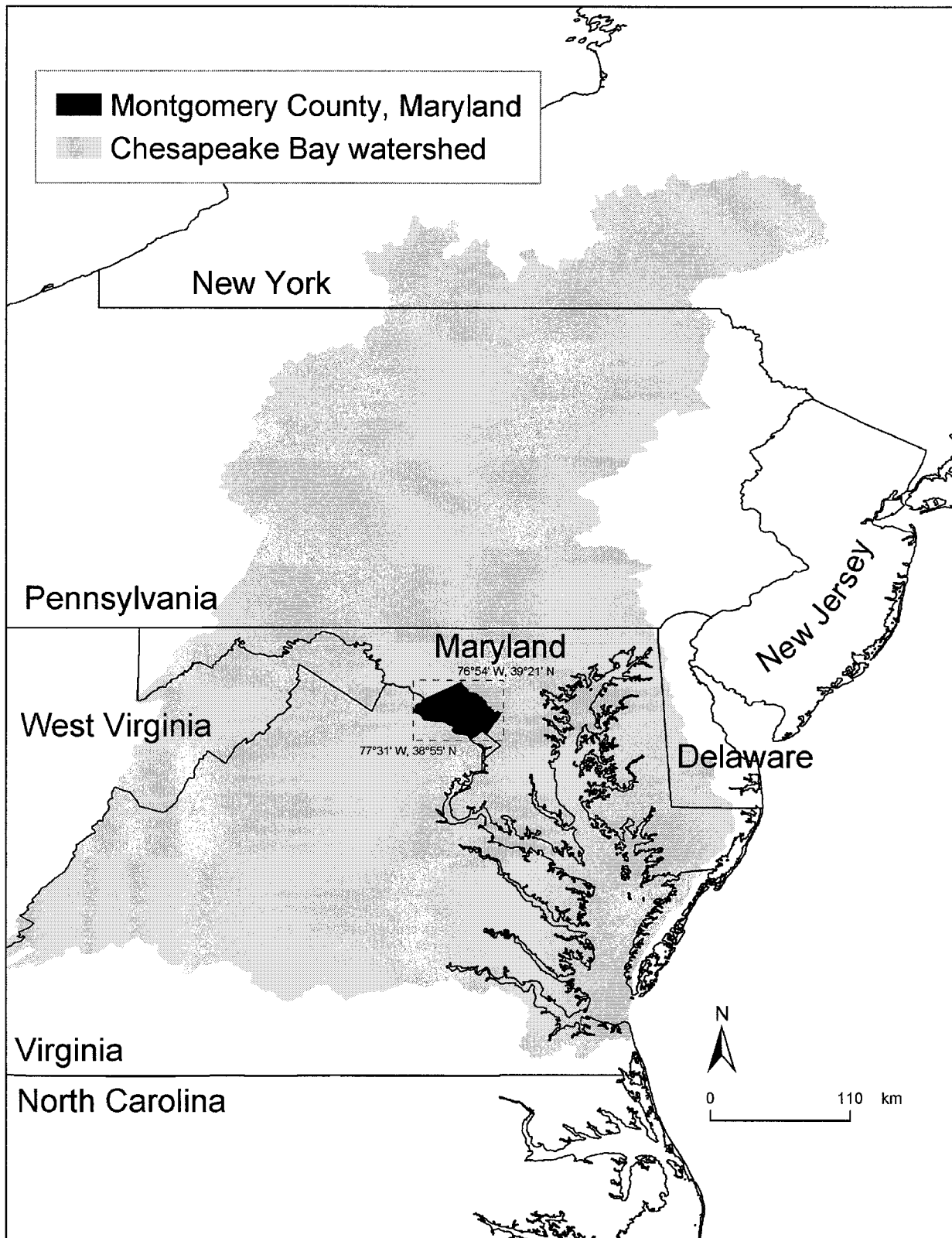


Figure 1. The Location of Montgomery County, Maryland, Within the Chesapeake Bay Watershed.



Seneca Creek, Sandy Branch on the Potomac, Cabin John Creek, Little Falls on the Potomac, Rock Creek, Anacostia River, Rock Gorge Dam, Brighton Dam, and Broad Run to Horsepen Branch Drainage. The study area lies within the Piedmont physiographic province and is characterized by silt loam, channery silt loam, and triassic loam soil types. This study analyzed watersheds that were further subdivided into 284 subwatersheds, comparable to 14-digit HUCs (1 km<sup>2</sup> to 47 km<sup>2</sup>), which are more suitable to management and restoration activities (MCDEP, 2001).

### Stream Health Data

Collaborators from the Montgomery County Department of Environmental Protection (MCDEP) and the Maryland-National Capital Park and Planning Commission (M-NCPPC) provided stream health data for the subwatersheds (Cameron Wiegand, MCDEP, October 2, 2002, personal communication; Mary Dolan, M-NCPPC, May 5, 1999, personal communication). They used an IBI for macroinvertebrate species and for fish species based on the ecological assemblages found in reference streams, developed and measured by the Maryland Department of Natural Resources (MD-DNR) (Stribling *et al.*, 1998; Roth *et al.*, 2004). The IBI for macroinvertebrate species was calculated based on the following variables: total number of taxa, biota index, ratio of scrapers, proportion of hypopsyche and cheumatopsyche to total Ephemeroptera, Plecoptera, and Trichoptera (EPT) individuals, proportion of dominant taxa, total number of EPT taxa, proportion of total EPT individuals, and proportion of shredders. The fish IBI was developed using the following variables: total number of species, total number of riffle benthic insectivores, total number of minnow species, total number of intolerant species, proportion of tolerant individuals, proportion of pioneering species, total number of individuals excluding tolerant, and proportion of diseased. The reference streams chosen were the most undisturbed streams in the county, and these were used to represent the best possible conditions. Baseline data were collected between 1996 and 2001. These IBI rankings were combined with physical data from the same sampling location (pH, temperature, DO) for a number of sampling stations within each subwatershed to produce a stream health ranking from 1 to 50 (Van Ness *et al.*, 1997). These sampling locations vary in the total amount of interior reaches that were included in the sample. The stream health rankings were then converted to narrative rankings of excellent, good, fair, and poor, with the streams in excellent health representing reference stream conditions (Figure 2).

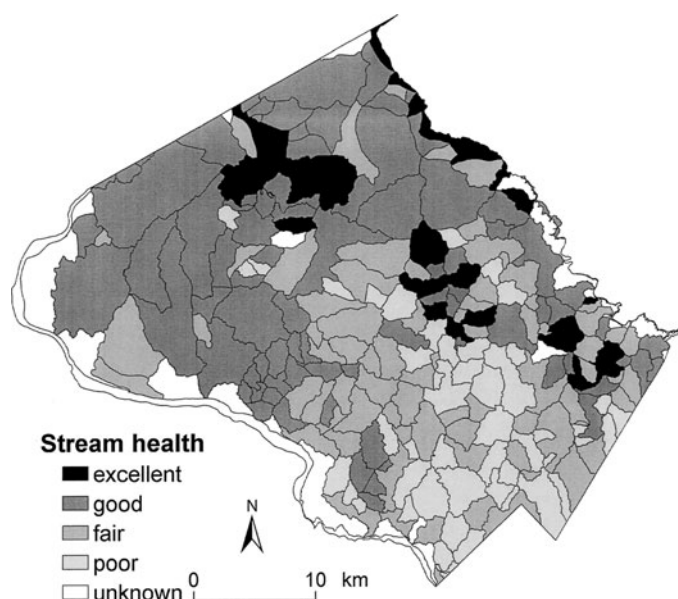


Figure 2. Watershed Stream Health Rankings as Developed by the Montgomery County Department of Environment and the Maryland Department of Natural Resources From a Combination of Physical and Biotic Stream Measurements.

Of the 284 subwatersheds, 66 were omitted from further analysis due to incomplete assessments or spatial coverage. This number includes those subwatersheds with more than 15 percent cloud cover at the time of satellite image acquisitions used to derive the land cover maps. In this respect the results differ from those summarized by Goetz *et al.* (2003) in their mapping assessments. The remaining 218 subwatersheds included 31 ranked as having excellent stream health, 77 good, 68 fair, and 42 poor. The stream reaches and associated subwatersheds were delineated and monitored by MCDEP and M-NCPPC so as to minimize spatial autocorrelation, although it is recognized that physical and biotic properties are cumulative as one moves downstream (Stribling *et al.*, 1998; Roth *et al.*, 2004).

### Land Cover Data

Eleven tiles of Space Imaging IKONOS “precision georeferenced” imagery were acquired between April 6, 2000, and May 23, 2001, and requisitioned through the National Aeronautics and Space Administration (NASA) Scientific Data Purchase program. The imagery covered a 1,313 km<sup>2</sup> area encompassing Montgomery County at 4 m resolution in four multispectral wavelength bands (blue, green, red, and near-infrared). The tiles are a mix of leaf-on (foliage expanded) and leaf-off (foliage absent) imagery acquired between early and late spring. Although the

IKONOS satellite has a pointable sensor allowing frequent repeat acquisitions, it was not possible to obtain completely cloud free imagery over the entire county during the 16-month acquisition period. Masks of clouds and cloud shadows were created manually by delineating affected areas in the imagery.

Maps of tree cover (Figure 3) and ISA (Figure 4) were derived from the imagery using a decision tree classification based on the individual wavelength bands and including the Normalized Difference Vegetation Index (NDVI), the Atmospherically Resistant Vegetation Index (ARVI), and the near infrared/blue ratio to discriminate specific land cover types (Goetz *et al.*, 2003). The image classification variables varied whether tree cover or ISA was the intended product. The classification trees were created with S-PLUS statistical software (Insightful Corporation, 1999), which uses a univariate algorithm to recursively threshold the training data into homogeneous groupings.

The training data for the ISA classification were vector planimetric coverages from the M-NCPPC (Mary Dolan, M-NCPPC, May 5, 1999, personal communication), including building and road footprints. For the tree cover map the training data were forest areas (> 60 percent tree cover) mapped in 1992 using a relatively large minimum mapping unit that captured densely forested areas. Both training datasets were created from visual interpretation of aerial photography and were preprocessed for accuracy to account for areas that had changed. Because some roads were obscured by trees in the satellite image ISA map, the classification result was combined with the rasterized planimetric data in order to provide more complete spatial coverage. The final tree and ISA maps capture changes in the land cover since 1992 and show more detail because of the fine spatial resolution of the imagery. Details on the creation and assessment of the tree cover and impervious surface maps from IKONOS imagery are reported by Goetz *et al.* (2003).

Impervious surface area maps from two other sources were incorporated in this study for comparison purposes. The first was from the Maryland Department of Planning (MDP, 2000), produced by assuming literature impervious surface coefficients for each of 14 land use types at a minimum mapping unit of 4 hectares (10 acres). The second was a 30 m digital ISA map created from Landsat 7 imagery at subpixel resolution (Goetz *et al.*, 2004). In the latter, each pixel has a value representing the proportion (percent) of that pixel occupied by impervious surfaces. The ISA map is similar to those being produced as part of the National Land Cover Database (Yang *et al.*, 2003) but was focused specifically on achieving

consistency across the Chesapeake Bay watershed rather than a National Land Cover Database mapping zone (of which there are portions of five within the Bay watershed). The purpose of incorporating these additional maps was to assess their utility relative to the finer resolution conveyed by the IKONOS satellite imagery. For example, the relation of ISA to water quality might be obscured when using ISA coefficients with a land use map because the amount of ISA within classes may vary greatly depending upon the amount of trees, grass, and other mixtures of land cover (McCauley and Goetz, 2004).

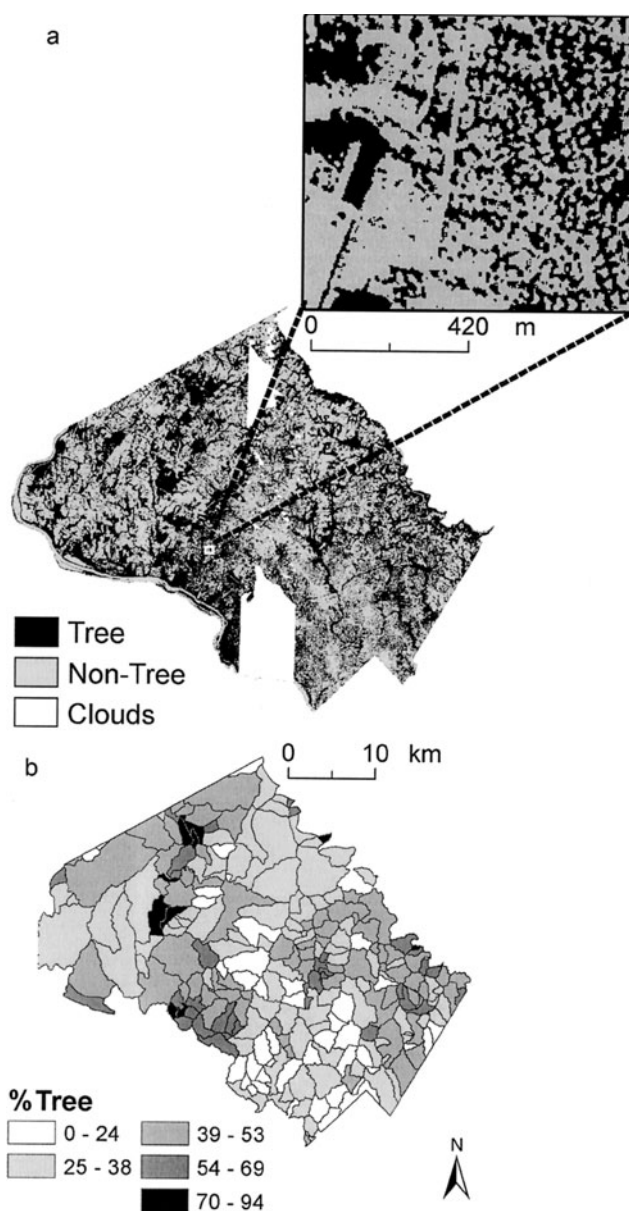


Figure 3. (a) Fine Resolution Forest/Nonforest Map of Montgomery County, Maryland, Created From IKONOS Imagery Acquired Between April 6, 2000, and May 23, 2001; and (b) Percent Tree Cover for Each of the Study Subwatersheds, Derived From the Data in Figure 3a.



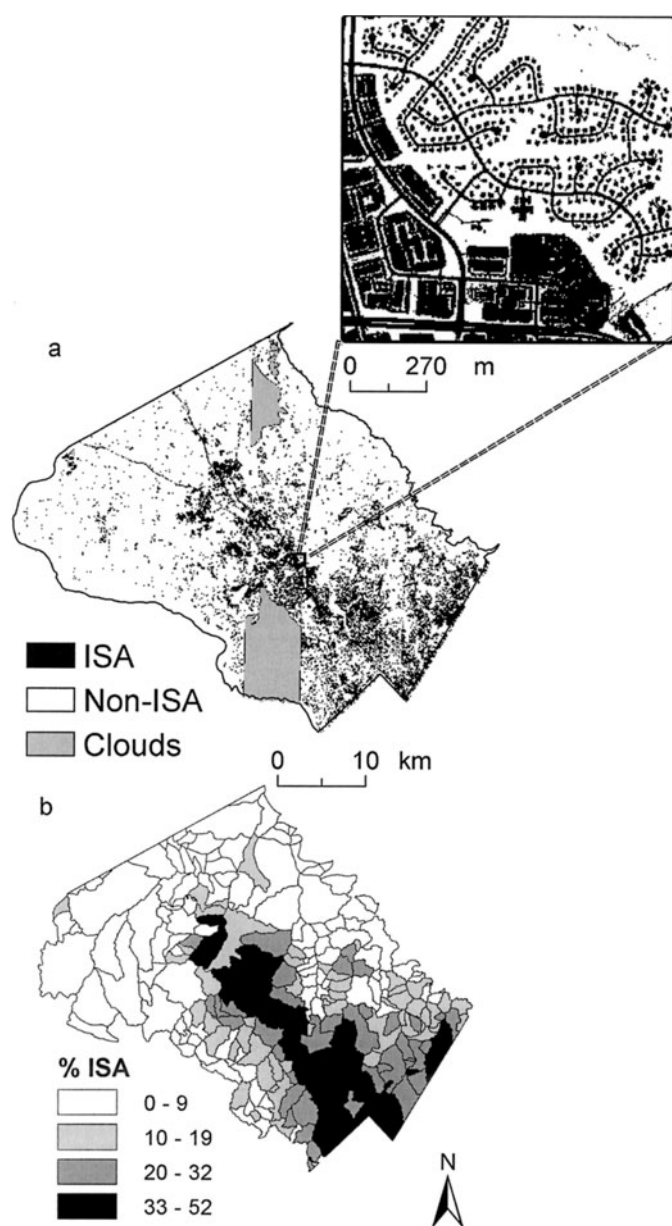


Figure 4. (a) Fine Resolution Impervious/Nonimpervious Surface Area Map Created From IKONOS Imagery Acquired Between April 6, 2000, and May 23, 2001; and (b) Percent Impervious Surface Area for Each of the Study Subwatersheds, Derived From the Data in Figure 4a.

Agricultural crop type maps were derived from multitemporal Landsat imagery and field level crop information in collaboration with the National Agricultural Statistics Service (NASS) (Michael Craig, NASS, May 22, 2002). The resulting map included corn, soybeans, winter wheat, and other crops (Figure 5) but was at a coarser resolution (30 m) than the digital tree cover or ISA image maps. Nonetheless, it represented the most accurate crop information available.

A digital elevation model (DEM) was created from a topographic map provided by Montgomery County. The vertical and horizontal resolution of the topographic map (< 30 cm) was used to create a 4 m resolution DEM (Figure 6), from which a grid of the percent change in slope between the cells was derived.

#### Land Cover Composition Metrics

Land cover composition metrics at the subwatershed and riparian buffer scales were derived from the digital image maps, including the percent of each subwatershed that was tree cover, ISA, and crop. Using the fine resolution (4 m) ISA map, the coarse resolution (30 m) percent ISA map, and Maryland Department of Planning ISA map, three different estimates of ISA for each subwatershed were derived for comparison. The area of each subwatershed and the mean percent slope for each subwatershed was also estimated for inclusion in the statistical models.

A vector hydrology layer provided by the county was used to create 30 m (100 ft) riparian buffers, since this is a common metric used for determining Chesapeake Bay restoration efforts. The tree cover map, the (4 m) ISA map, and the percent change in slope map were intersected with the buffer coverage to calculate for each subwatershed buffer zone the proportion of tree cover, ISA, and mean slope. The percent crop in the buffer was not calculated because the coarser resolution (30 m) of the crop classification would preclude accurate estimates.

To examine the relevance of landscape configuration on the links between land cover and stream health, a number of configuration metrics were developed from the fine resolution ISA map. For each subwatershed the distance of the nearest impervious surface patch to the centerline of the stream channel was calculated. The mean distance from all the impervious surface patches was also calculated and then divided by the percent of impervious surface to create a metric that captured the spatial configuration of the impervious surface area in a subwatershed. The latter metric was developed to account for the fact that as impervious surfaces increase, there is a higher probability that they will be close to a stream. This normalized metric addresses configuration without being overly influenced by the area of the impervious surface in the subwatershed.

Using the DEM and a direction grid derived from the DEM, flow paths from the impervious surface patches to the centerline of the stream channel were also developed. The flow path grid was created in ArcGIS workstation with the watershed component of the GRID module (ESRI, 1998). The algorithm used to

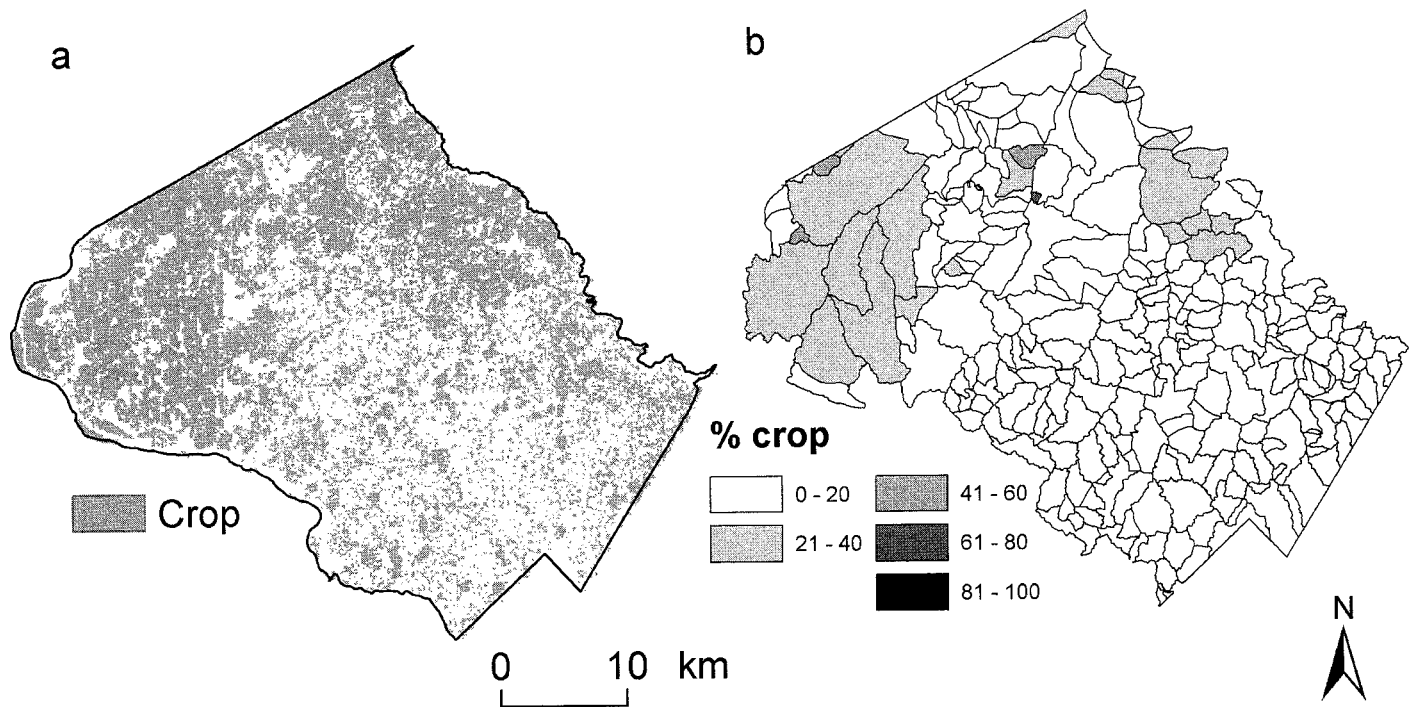


Figure 5. (a) Crop Cover Map of Montgomery County Created From Supervised Classification and National Agricultural Statistical Service Field Data; and (b) Percent Crop for Each of the Study Subwatersheds, Derived From the Data in Figure 5a.

compute flow direction was of the single path method, and therefore multiple flow paths were not considered in the analysis. The proportion of each flow path that was occupied by trees and impervious surface area was then calculated to determine whether simple metrics representing some aspect of impervious surface configuration were predictive of stream health ranking.

To further examine the role pattern plays in the landscape, two landscape pattern metrics, contagion and clumpiness, were calculated for the impervious surface patches in each subwatershed (McGarigal and Marks, 1995). These two Fragstat indices describe the spatial configuration of the impervious surface areas in terms of their dispersion and aggregation across the landscape. The contagion index is a landscape-level metric, while the clumpiness index is a class-level metric. The contagion index, which can vary in a theoretical landscape from 0 to 100, is the observed number of like adjacencies divided by the possible number of like adjacencies for each of the image elements (pixels). Zero represents the most disaggregated landscape and 100 a single patch. The clumpiness index, which can vary from -1 to 1, also utilized the number of like adjacencies between impervious cells, but it accounts for the inherent correlation between the proportion of the landscape that was impervious and the increasing probability of having like adjacencies. As land cover percent increases, the number of

like adjacencies increases. To account for this inherent correlation, the proportional deviation of the number of like adjacencies was calculated relative to a random landscape. At negative one the landscape would be maximally disaggregated, at zero it would be randomly distributed, and at one it would be maximally aggregated.

#### *Logistic Regression Models*

Logistic regression models were developed in SAS (SAS Institute Inc., 2002) to predict stream health rankings with potential land cover and landscape metrics. Logistic regression permits prediction of categorical dependent variables, in this case the stream health rankings. The logistic regression models were polytomous with ordinal dependent variables. Values in a logistic regression model are chosen using maximum likelihood to predict the probability of a given category. Advantages of this approach include the relaxation of assumptions regarding normally distributed or homoscedastic datasets. A homoscedastic dataset assumes that the variance of the error is the same for differing independent variables. The distribution of the dependent variable, however, influences the percent of variance explained, prohibiting calculation of variance explained using traditional ordinary least squares techniques (Hosmer and Lemeshow,

1989). An ordinary least squares regression creates a linear model from the independent variables that explains the maximum amount of variance in the dependent variables and establishes the predictive power of the independent variables. Therefore, the adjusted R-square value of a logistic regression model is not equivalent to the coefficient of determination or R-square value from an ordinary least squares regression model. Instead, an odds ratio conveys the increase or decrease in probability that a unit change in the independent variable has in the probability that the category of interest will occur.

The adjusted R-square value reported is a ratio of the Cox and Snell R-square value to the maximum R-square value possible in the model. Values of the R-square between 0.2 and 0.4 are considered a good fit (Hosmer and Lemeshow, 1989). For each of the logistic regression models the Wald statistic, a test of the significance of the regression coefficient against a chi-square distribution, was also reported, and a C criterion goodness of fit, which represents the percent of cases out of all possible that the model assigns a higher probability to the correct to an incorrect possibility. The value of the latter ranges from 0.5 to 1, with the lower value representing the chance assignment of the correct probability.

Rather than eliminate correlated variables, which were calculated using Spearman rank correlation coefficients in SAS, the logistic models were allowed to include in a stepwise fashion those most significant as predictors of stream health. The stepwise approach combined both forward selection and backward elimination, with a 0.05 significance level for entering the model. This approach was also useful because the most relevant scale of analysis was unknown, and the metrics at the subwatershed and riparian buffer scale have the potential to isolate different processes that may influence stream health. From a management perspective, these can be considered different possible strategies, which were simulated by withholding selected variables.

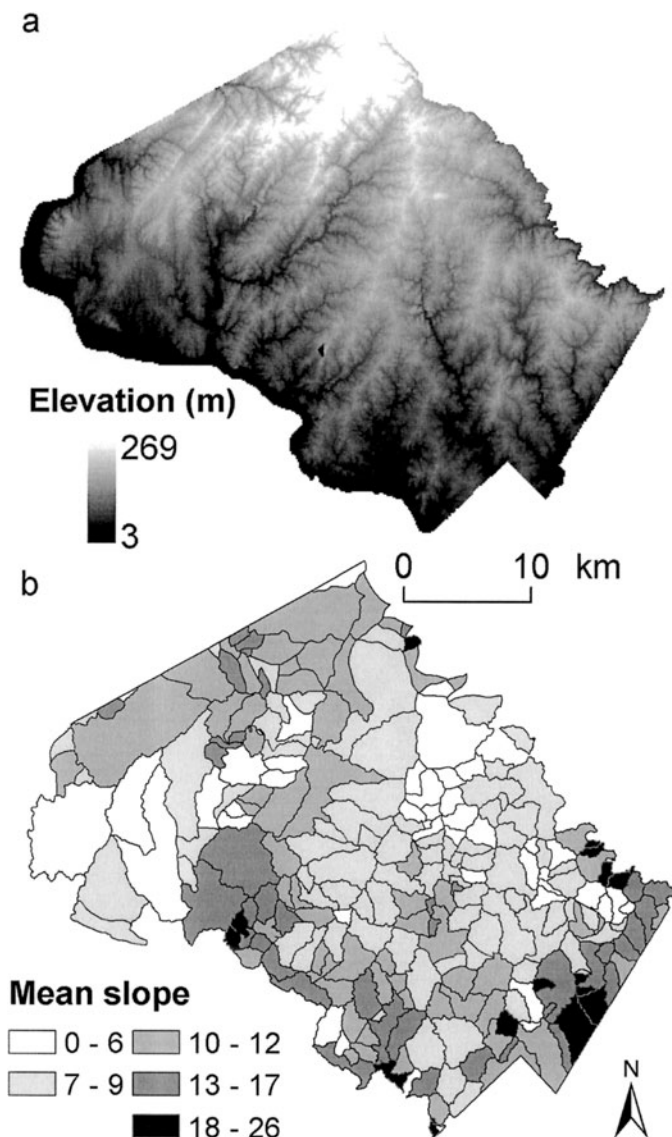


Figure 6. (a) A Fine Resolution Digital Elevation Model Created From a 5-Foot (1.5 m) Contour Map Provided by the M-NCPPC; and (b) The Mean Percent Change in Slope for Each Subwatershed.

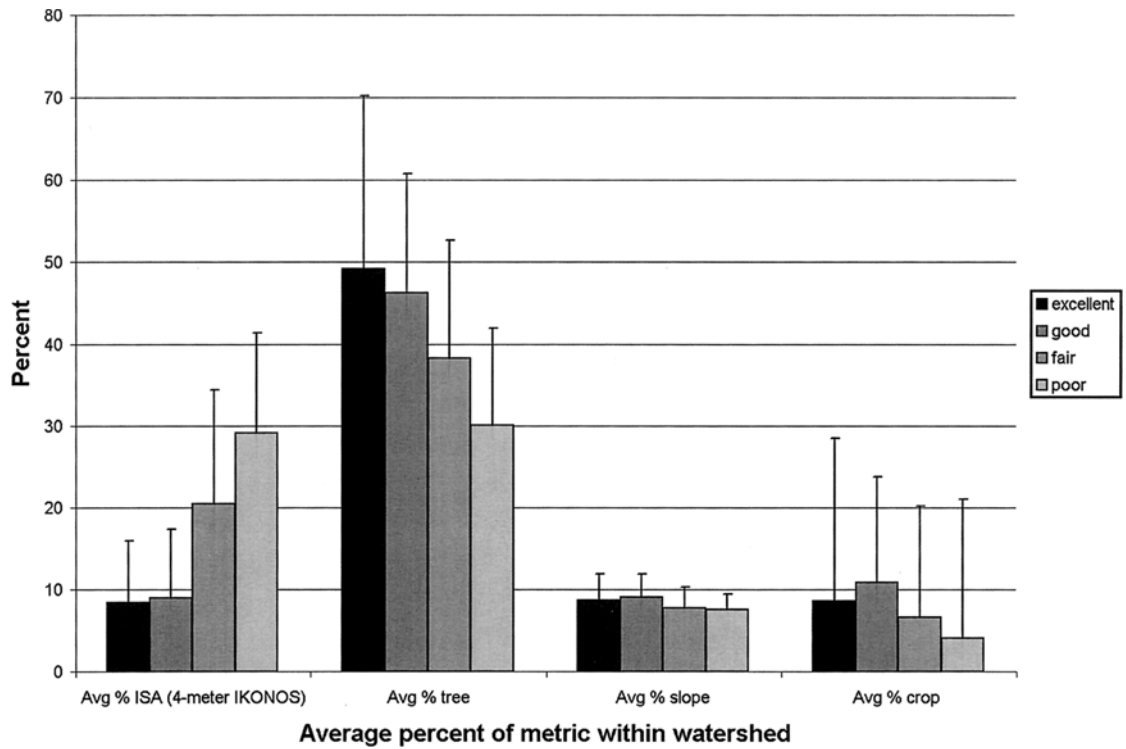
## RESULTS

### *Watershed and Riparian Zone Analysis*

The watersheds in Montgomery County exhibit a wide range of land cover composition and configuration (Figures 3 through 6). The amount of ISA derived from the fine resolution map (4 m) varied from 0 percent to 52 percent, while the percentage of tree cover varied from 0 percent to 94 percent (Figure 7a). When the subwatersheds were grouped by stream health ranking (excellent, good, fair, poor), it was apparent that the average percent ISA increased from excellent to poor rankings, while the average percent tree cover decreased (Figure 7). In the riparian buffer zone tree cover ranged from 0 percent to 98 percent, the ISA varied from 0 percent to 32 percent, and the mean percentage slope from 3 percent to 26 percent (Figure 7b). The percent of the buffer occupied by trees decreased, and the percent of ISA in the buffer increased with stream ranking, although a slight but insignificant decrease in percent ISA in the buffer occurred between the excellent and good rankings.



(a)



(b)

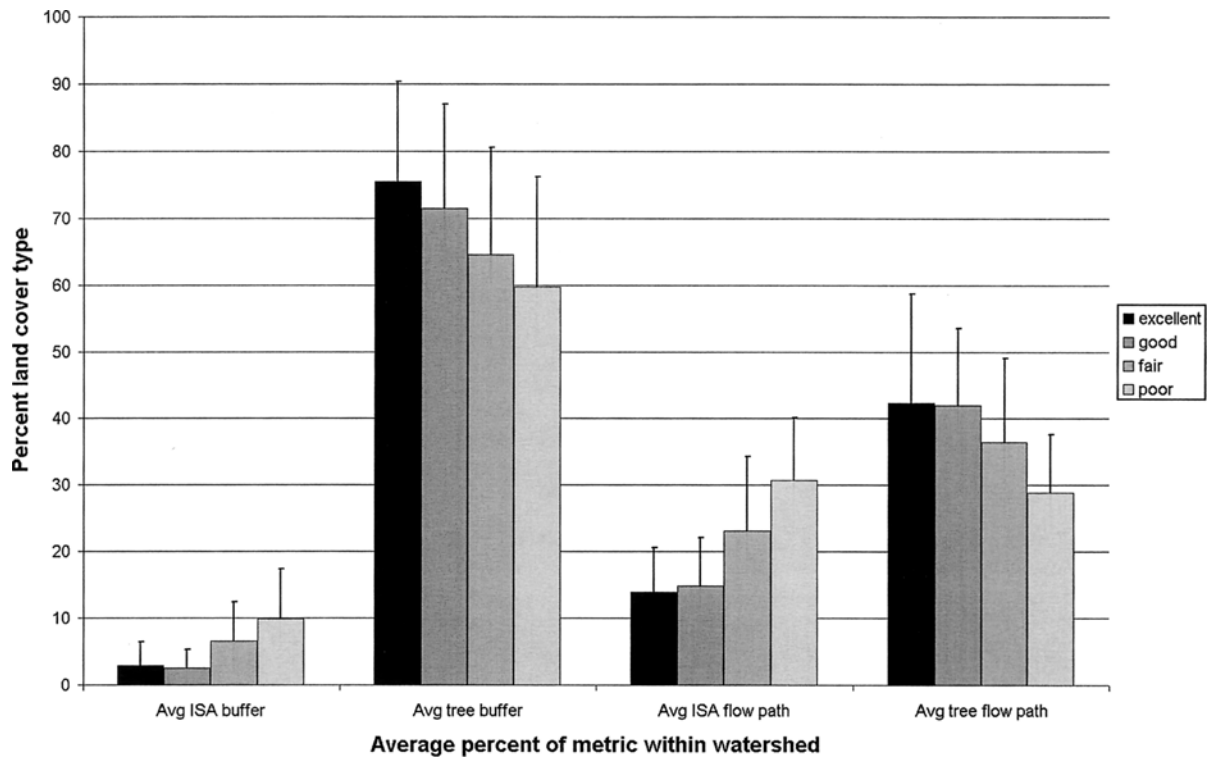


Figure 7. The Average Percent of Each Land Cover Type Within the Subwatersheds, Partitioned by Stream Health Ranking (a) for the Entire County and (b) for Only Those Areas Within the Stream Buffer or Flow Path.

The percentage of crop cover in the subwatersheds varied from 0 percent to 66 percent, and the mean percent change in slope per watershed ranged from 4 percent to 16 percent (Figure 7a). Neither the average percent crop cover nor the mean slope in the watersheds showed any consistent trend with stream health ranking.

Some land cover and composition metrics were correlated (Table 1) and thus were not independent estimators; these included the percent ISA in a watershed and in the buffer zone (0.80) and the percent tree cover in the subwatershed and the buffers (0.74). Moreover, the impervious surface area and the tree cover area in the subwatershed were inversely correlated (-0.56); thus as the percent ISA in a subwatershed increased, the percent tree cover decreased (Figure 8). The exception to this, which introduces some variability in the relationship, was watersheds dominated by agriculture that had relatively low amounts of impervious and tree cover. Because ISA and tree cover relate to stream health in different ways, they were both included in the logistic models, but forced elimination tests helped to assess their relative importance.

The logistic regression model analyses using the watershed and riparian buffer metrics as the independent variables, and the stream health rankings as the categorical dependent variables, selected the percent ISA in the watershed as the primary predictive variable ( $r^2 = 0.33$ ,  $p < 0.0001$ ), followed by the percent tree cover ( $r^2 = 0.35$ ,  $p = 0.04$ ; Model 1 in Table 2). The latter added relatively little to the overall model predictive power (2 percent) but was consistently included as a statistically significant variable. Using different sources of impervious data had little effect on the overall model outcome. The subpixel ISA maps created from the 30 m Landsat imagery and the MDP land use map combined with impervious surface coefficients averaged similar levels of imperviousness as the fine resolution (4 m) IKONOS ISA map.

To test the relationship between stream health and the land cover composition variables in the riparian buffer zone, a logistic regression model was developed using only the impervious surface, tree cover, and slope metrics within the buffer as the independent variables. The resulting model (Model 2 in Table 2) selected the percent impervious surface in the buffer first ( $r^2 = 0.23$ ,  $p < 0.01$ ), the percent tree cover in the buffer second ( $r^2 = 0.24$ ,  $p < 0.01$ ), and then the percent change of slope in the buffer (whole model  $r^2 = 0.27$ ). This model had lower overall explanatory power than that including the subwatershed scale information ( $r^2 = 0.35$ ,  $p < 0.01$ ).

In subwatersheds with different dominant land uses, the mechanisms by which stream health is affected may differ. Two different logistic regression

TABLE 1. Spearman Rank Correlation Coefficients of the Composition and Configuration Variables.

	Percent Watershed	Percent Tree Watershed	Mean Slope Watershed	Percent Crop	Percent ISA Buffer	Percent Tree Buffer	Percent Mean Slope Buffer	Distance Nearest ISA	Percent ISA Flow Path	Percent Tree Flow Path	Contagion Clumpiness
Percent Tree Watershed	-0.56*	1									
Mean Slope Watershed	-0.33*	0.61*	1								
Percent Crop	-0.26*	-0.59*	-0.50*	1							
Percent ISA Buffer	0.80*	-0.51*	-0.29*	0.21*	1						
Percent Tree Buffer	-0.43*	0.74*	0.45*	-0.27*	-0.56*	1					
Percent Mean Slope Buffer	0.11	0.27*	0.71*	-0.23*	0.03	0.33*	1				
Distance Nearest ISA	-0.45*	-0.34*	-0.19	0.31*	0.34*	0.17	0.05	1			
Percent ISA Flow Path	0.97*	-0.52*	-0.29*	0.31*	0.76*	-0.39*	0.15	0.49*	1		
Percent Tree Flow Path	-0.56*	0.80*	0.46*	-0.43*	-0.48*	0.64*	0.16	-0.40*	-0.56*	1	
Contagion	-0.96*	0.50*	0.34*	0.38*	-0.74*	0.37*	-0.09	-0.42*	-0.96*	0.52*	1
Clumpiness	0.28*	-0.02	-0.09	-0.63	0.29	-0.14	-0.11	-0.13*	0.26*	-0.05	-0.30*

\*Indicates significance at the  $< 0.001$  level.

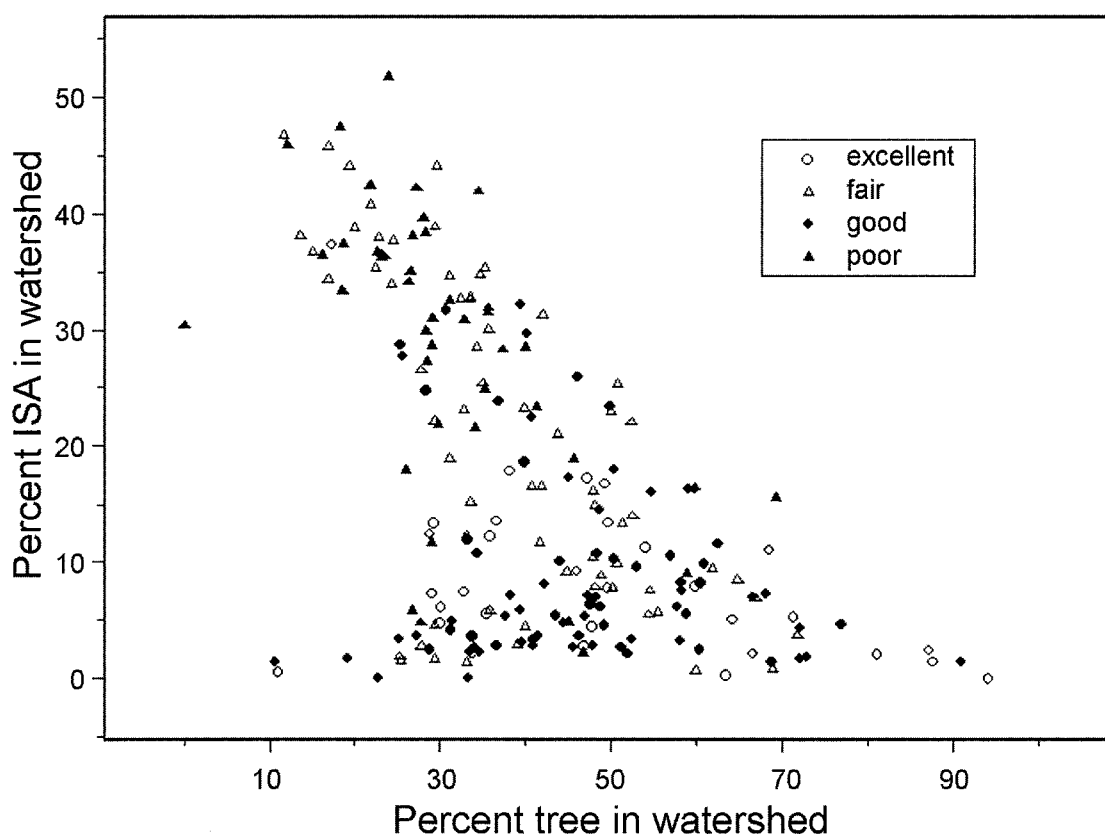


Figure 8. The Percent Impervious Area Plotted Against the Percent Tree in Each Subwatershed.

models were calculated with two samples of the subwatersheds to determine if the stream health was related to different variables depending on the dominant land cover type (Models 3 and 4 in Table 2). Subwatersheds with greater than 20 percent impervious surface area ( $n = 76$ ) were considered catchments where urbanization dominated land use. Subwatersheds with greater than 20 percent crop area were considered primarily agricultural ( $n = 22$ ). For urbanized watersheds the model included the percent tree cover in the watershed ( $r^2 = 0.07$ ,  $p = 0.02$ ) and then the percent crop cover ( $r^2 = 0.15$ ,  $p = 0.02$ ). For agricultural watersheds the primary predictors were the mean slope ( $r^2 = 0.16$ ,  $p = 0.02$ ) and the area of the watershed ( $r^2 = 0.35$ ,  $p = 0.07$ ).

Because land managers and planners may not have ISA data available to them, a logistic regression model with only the tree cover variables was also developed (Model 5 in Table 2). In this case the sole variable selected was the percent tree cover in the watershed ( $r^2 = 0.19$ ,  $p < 0.0001$ ). When only ISA data were available, the predictive power of the model was much greater than with tree cover alone ( $r^2 = 0.33$ ). In another scenario a land manager might not have ISA data but may have information on many other aspects of the watershed. A logistic regression model run to

simulate this scenario included the percent tree cover in the watershed, the percent tree cover in the buffer, the percent crop, and the mean slope in the buffer as predictor variables (Model 6 in Table 2). In this case the percent tree cover in the subwatershed had the highest predictive power ( $r^2 = 0.20$ ). Percent crop and mean slope in the buffer were also selected as significant variables ( $r^2 = 0.32$ ). This scenario model had nearly the same predictive power as the model including all these variables as well as the ISA information ( $r^2 = 0.35$ ).

#### *Land Cover Configuration Analysis*

The resolution of the IKONOS digital tree cover map revealed individual and groups of trees in neighborhoods, as well as large blocks of contiguous tree cover (i.e., forest) (Figure 3). The IKONOS map of ISA captured individual building footprints, driveways, and roads (Figure 4). The spatial resolution of the data made it possible to consider questions regarding the configuration of the impervious surfaces and tree cover in subwatersheds and the cover composition within the riparian buffer zone, thus how these together influenced stream health (Table 3). When the



TABLE 2. Logistic Regression Model Results and Fit Statistics.

	Model Adjusted R <sup>2</sup>	Wald Chi-Square	P (maximum likelihood)	C Criterion
<b>Landscape Composition Metrics</b>				
(1) <b>Watershed and Riparian Buffer Metrics</b>				0.747
Percent ISA Watershed (IKONOS 4 m)	0.33	< 0.0001	< 0.0001	
Percent Tree Watershed	0.35	0.041	0.03	
(2) <b>Buffer Only</b>				0.736
Percent ISA Buffer	0.23	< 0.0001	0.0002	
Percent Tree Buffer	0.24	0.07	0.0034	
Mean slope Buffer	0.27	0.01	0.0077	
(3) <b>&gt; 20 Percent ISA (N = 76)</b>				0.699
Percent Tree Watershed	0.07	0.03	0.02	
Percent crop	0.15	0.01	0.02	
(4) <b>&gt; 20 Percent Crop (N = 22)</b>				0.840
Mean Slope Watershed	0.16	0.07	0.07	
Watershed Area	0.35	0.04	0.10	
Percent ISA Buffer	0.46	0.06	0.02	
(5) <b>Forest Only</b>				0.686
Percent Tree Watershed	0.19	< 0.0001	< 0.0001	
(6) <b>Without ISA</b>				0.737
Percent Tree Watershed	0.2	< 0.0001	< 0.0001	
Percent Crop	0.29	< 0.0001	< 0.0001	
Mean Slope Buffer	0.32	< 0.0001	0.0064	
<b>Landscape Configuration Metrics</b>				
(7) <b>Without Percent ISA Watershed</b>				0.739
Percent ISA Path	0.31	< 0.0001	< 0.0001	
Percent Tree Watershed	0.34	0.0195	0.0137	
(8) <b>Without Percent ISA Path</b>				0.747
Contagion	0.31	< 0.0001	< 0.0001	
Percent Tree Watershed	0.34	0.0122	0.01	
<b>Percent ISA in Watershed From Different Sources</b>				
IKONOS (4 m)	0.33	< 0.0001	< 0.0001	0.741
MDP Coefficients (4 ha)	0.30	< 0.0001	< 0.0001	0.742
Landsat (30 m)	0.31	< 0.0001	< 0.0001	0.743

Note: Sample size is 218 except where indicated.

flow path metrics were added to the logistic regression model, including the path metrics as independent variables, the percent impervious surface in the subwatershed remained the most important predictive variable. When the percent impervious surface in the subwatershed was excluded from the model (Model 7 in Table 2) the percent impervious surface in the flow path was the first variable selected ( $r^2 = 0.31$ ,  $p < 0.0001$ ). The two values were highly correlated (0.97), as was the percent tree cover in the flow path and the subwatershed (0.80). The impervious surface distance metrics (mean distance from impervious surface

divided by percent impervious and minimum distance from impervious surface to stream) were not selected as significant predictors.

The observed contagion values varied from 16 to 100 (Figure 9), and the clumpiness (clumpy) index varied from -1 to .847 (Figure 10). A logistic regression model calculated including the other landscape pattern and composition metrics and the contagion and clumpiness indices did not select either landscape metric as a significant predictor. When another logistic regression model was calculated (Model 8 in Table 2) excluding the percent of impervious area in the

TABLE 3. Average Values for Landscape Configuration Metrics.

Landscape Configuration Metric	Stream Quality			
	Excellent	Good	Fair	Poor
Average Distance to ISA (m) / Percent ISA in Watershed	79.5	44.8	29.2	13.5
Average Nearest Distance to ISA (m)	0.18	1.56	0.10	0.19
Average Percent ISA in Flow Path	13.9	14.8	23.1	30.7
Average Percent Tree in Flow Path	42.3	42.0	36.4	28.8
Average Clumpy Index	0.65	0.63	0.68	0.67
Average Contagion Index	70.9	69.6	49.4	54.5

subwatershed but including the contagion and clumpiness indices, the contagion index was the first variable selected ( $r^2 = 0.31$ ,  $p < 0.0001$ ). The contagion metric was, however, highly correlated (-0.96) with the percent impervious surface in the subwatershed. The clumpiness index was not highly correlated with the percent impervious surface in the subwatershed (0.40), and it was not significant in any logistic regression model.

## DISCUSSION

Several studies in Maryland that examined the effect of urbanization on biotic communities have found that stream degradation starts between 10 percent and 15 percent ISA (Klein, 1979; Boward *et al.*, 1999). Klein (1979) suggests that above 30 percent impervious surface cover, stream health was more likely to be in poor condition. In the subwatershed assessment methods of the Center for Watershed Protection (Schueler, 1994; Zeilinski *et al.*, 2002) streams with more than 10 percent impervious surface area are denoted as losing sensitive species, between 11 and 25 percent as impacted, and more than 25 percent nonsupporting. The results of this study indicate that watersheds in excellent health averaged less than 8 percent ISA, watersheds in good health averaged less than 10 percent ISA, those rated fair averaged less than 20 percent ISA, and those with a poor health ranking exceeded 29 percent ISA. A few subwatersheds in this study had greater than 15 percent impervious surface area but were still rated excellent, indicating that landscape configuration was important in some cases. These thresholds were calculated from large sample sizes, conveyed not just by the substantial number of subwatersheds studied but also by the fine resolution of the image maps. As such, the percentage values reflect statistically significant differences between rankings with some precision.

When considering only the composition of land cover within a watershed, the percent ISA was the primary predictor of stream health. When the configuration of the ISA was considered, the results of this study indicate that the primary influence on stream health was the amount of impervious surface in a subwatershed rather than its configuration. When predicting categorical measures of stream health, measures of ISA configuration added little to the statistical models of conditions affecting stream health. The results also indicate that land cover in the buffer zone was a significant predictor of stream health, but land cover throughout the watershed was a more powerful predictor. Some of the observations regarding the relative importance of landscape configuration were likely masked by channelization and the presence of storm drains that bypass the buffer zone and more directly connect the stream to the impervious surface areas. This has the effect of placing greater relative importance on the total amount of impervious area across watersheds. These results thus support evidence that creating built environments with less ISA or reducing the impacts of ISA through mitigation measures would benefit stream water quality and associated biotic health.

The direct mechanisms affecting the biotic communities that are used as indicators of stream health could not be fully elucidated in this study without more comprehensive watershed modeling. Possible reasons for streams with degraded stream health are many, including nonpoint source pollution, point source pollution, hydrologic alteration, stream incision and sediment load changes, altered temperature regimes, and modified biotic interactions. Moreover, past studies indicate that the influence of land use on stream health is scale dependent (Lammert and Allan, 1999; Wang *et al.*, 2001). Interpretation of the results of this study indicates that the processes most affecting stream integrity in these watersheds were those that represent land uses at the watershed scale.

In the analysis where the subwatersheds were stratified by dominant land cover type, the smaller

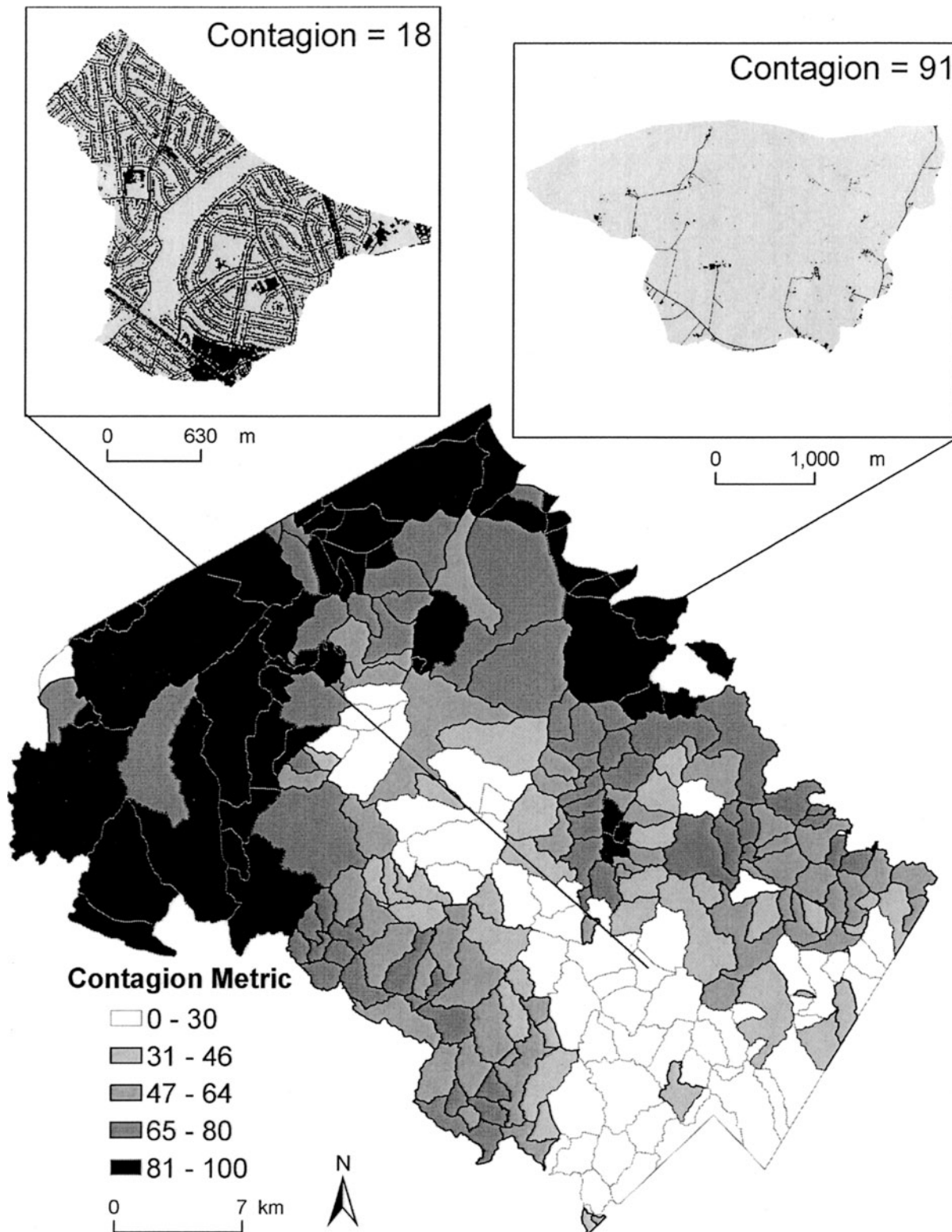


Figure 9. The Contagion Index for the Impervious Area Within Each Subwatershed, Where Contagion Increases as the Patch Adjacencies Become Increasingly Even (more uniform).



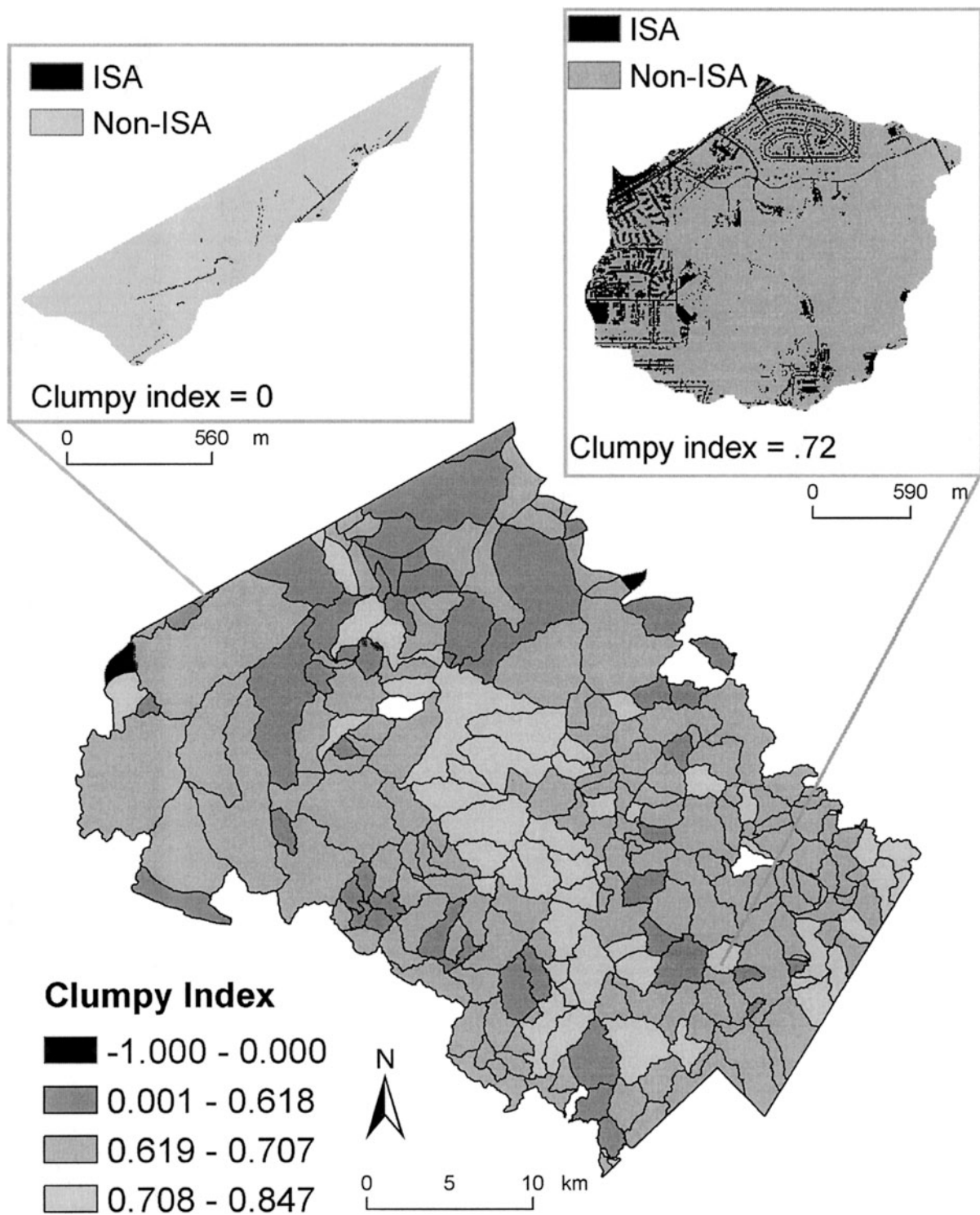


Figure 10. The Clumpiness Index for the Impervious Surfaces Within Each Subwatershed, Where Clumpiness Increases as the Landscape Features Become More Spatially Aggregated.

sample size reduced confidence in the statistical significance of the selected variables. In the urbanized watersheds, for example, little variability in stream health rankings existed after impervious surface

percentage reached 20 percent. At that point most of the subwatersheds were ranked either fair or poor. Moreover, as watersheds become more urbanized, stormwater runoff is typically routed through pipes

and storm drains and thus would not follow its natural path to the stream. In these cases, metrics intended to model streamflow path are impractical without knowledge of the location of storm drains or mitigation measures such as stormwater retention ponds (data that were unavailable).

If only tree cover data were available for prioritization of stream restoration or conservation areas, the explanatory power of the predictions would be limited. When tree cover, crop, and elevation data are available, the explanatory power of the predictions increases but only by including these additional variables. The results indicate that ISA information would be a valuable resource for a land use planner and that simply knowing the amount of ISA in a subwatershed is more useful than knowing the patterns of dispersion or aggregation. The mean slope in the buffer and in the watershed metrics were sometimes selected as significant variables but with little explanatory value for the study area. In watersheds with little tree cover, the ISA or agricultural land uses on steep slopes would likely be more important due to increased erosion of stream channels and associated sediment loading (Snyder *et al.*, 2003).

These results have practical implications. Montgomery County is one of the more proactive jurisdictions within the Chesapeake Bay watershed, promoting active land preservation and watershed protection programs. Maryland, in turn, is at the forefront of the Chesapeake Bay restoration effort. It is one of the signatories of the Chesapeake Bay 2000 Agreement (C2K), which sets water quality improvement goals such as a 40 percent reduction in nutrient input to the Bay and creation of 2,010 miles (3,350 km) of forested riparian buffers by the year 2010. The Bay agreement espouses the need to "compile information and guidelines to assist local governments and communities to promote ecologically based designs in order to limit impervious cover in undeveloped and moderately developed watersheds, and reduce the impact of impervious cover in highly developed watersheds."

In this study the IKONOS imagery was available to develop a high-resolution map of ISA, yet this advanced analysis is not always possible or practical. Many municipalities have access to land use data, and the comparisons in Table 2 indicate that accurate impervious coefficients associated with land use classes may provide a level of predictive capability comparable to a 4 m product. For areas where an existing land use map is not available, 30 m Landsat Thematic Mapper products like those recently produced for the Chesapeake Bay watershed (Goetz *et al.*, 2004) and elsewhere (Yang *et al.*, 2003) can be equally adequate. The stepwise logistic regression model results indicate that the fine resolution image map had slightly

higher predictive power than the MDP land use coefficients based map or the 30 m ISA map, although the increase in model performance might not be considered sufficient to warrant the added cost of acquisition and development. This may not be the case in other locations, depending on the accuracy of the land use maps and the appropriateness of the ISA coefficients assigned to the land use categories (e.g., Dougherty *et al.*, 2004). The fine resolution data did, however, allow for detailed consideration of landscape configuration variables and land use within narrow (30 m) riparian buffer zones that otherwise would have not been practical. Although the landscape configuration variables did not prove highly significant for predicting stream health in most watersheds analyzed, most likely because of storm drains bypassing the buffer zone, they are potentially important metrics for consideration of stormwater management pollutant mitigation and stream restoration efforts.

The results of this study have demonstrated the utility of impervious surface data across spatial scales for the development of guidelines relevant to stream health. The Chesapeake Bay Program (CBP) is operating under a directive to create innovative ways to manage stormwater on public lands as an example to private landholders. By 2006 the CBP is to have installed 60 innovative stormwater management technologies on public land holdings that promote infiltration and prevent pollution (Chesapeake Bay Program, 2000). The findings from this study indicate that minimizing the amount of ISA in a watershed or mitigating its negative impacts through various management practices will aid the preservation and restoration of stream health.

Areas for future research as a result of this work are numerous, including incorporation of stream reach variability information not captured at the spatial and temporal scale of the subwatershed. The averaging and scaling of the stream reach measurements to the subwatershed scale may have confounded relationships apparent at finer scales (Richards *et al.*, 1997). The correlative nature of the metrics used and the categorical nature of the stream health rankings could also mask relationships between land cover configuration and stream biotic measurements. Moreover, management practices such as stormwater retention ponds and/or stream restoration efforts may influence these relationships. Other factors, such as instream habitat or point source pollution, not easily identified from imagery, could dominate disturbance within the stream. The availability of the fine resolution image data will allow us to explore these relationships with stream reach scale measurements, where they exist, and further assess the efficacy of increasingly relevant policies that fall under the umbrella of Low Impact Development, Green

Infrastructure, Best Management Practices, and Smart Growth.

## CONCLUSION

Land use composition and landscape configuration variables have practical application to a wide range of increasingly relevant watershed and stream management goals as a greater number of areas across the nation undergo conversion to residential and commercial development. This study used data from 218 very small watersheds (1 km<sup>2</sup> to 47 km<sup>2</sup>) and logistic regression models to predict categorical stream health rankings from a number of land cover and landscape metrics derived from fine resolution (4 to 30 m) satellite imagery. In many different scenarios the percent impervious surface area was consistently the most important predictive variable. The second most important variable was typically the percentage of tree cover in the watershed or the percent tree cover in the riparian buffer zone, and these two variables were positively correlated. The importance of impervious areas was likely influenced by the existence of storm drains that bypass buffer zones and effectively connect the stream to the built environment. If fine resolution ISA information were not available, ISA information from the other sources tested appeared to be equally useful as predictors of stream health at the subwatershed level. When the ISA information was not available (withheld), landscape configuration metrics were selected as significant alternative predictors, although with reduced overall explanatory power. The amount of ISA within the watershed conveyed more information than landscape configuration metrics derived from it, but inclusion of the latter always improved predictive capability. The additional information provided by landscape configuration and riparian buffer zone cover was facilitated by the use of metrics derived from the fine-resolution imagery, indicating a potentially valuable application of these datasets to augment landscape metrics based on categorical maps of land use alone.

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